



Detached Eddy Simulations of Hypersonic Transition

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Objective



- Investigate the feasibility of using CFD in general, DES in particular, for prediction of roughness-induced boundary layer transition to turbulence and the resulting increase in heat transfer



➤ *Threat of overheating the delicate RCC wing leading edges was real.*

Hardware



- NASA Advanced Supercomputing Facility enables fine-grid unsteady turbulent flow simulations.



Pleiades
SGI ICE
56,832 Intel Xeon Cores
673 TFlops, 75 TB Memory

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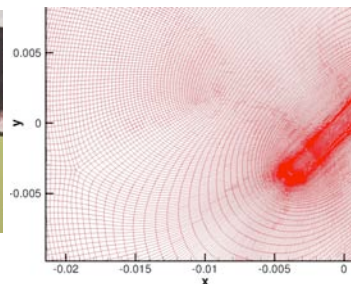
Software



- US3D code – Unstructured, parallel, finite-volume Navier-Stokes solver for thermo-chemical non-equilibrium hypersonic flows
- Detached Eddy Simulations (or WMLES) – Hybrid RANS/ LES approach
- Optional low-dissipation numerics



Wind tunnel model (1 mm high) compared with the Shuttle trip (6.35 mm high)



Unstructured hexahedral grid near the trip

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Inviscid Flux Evaluation



$$\frac{\partial U}{\partial t} + \nabla \cdot (\vec{F} - \vec{F}_v) = W$$

Navier-Stokes equations for a mixture of species in conservation law form

Steger-Warming Flux Vector Splitting

$$F = F^+ + F^- = R^{-1} \Lambda^+ R U + R^{-1} \Lambda^- R U$$

$$F_{i+1/2} = (R^{-1} \Lambda^+ R)_i U_i + (R^{-1} \Lambda^- R)_{i+1} U_{i+1}$$

At a cell face

Modified Steger-Warming Flux Vector Splitting

$$F_{i+1/2} = (R^{-1} \Lambda^+ R)_{i+1/2} U_i + (R^{-1} \Lambda^- R)_{i+1/2} U_{i+1}$$

Lower dissipation!

$$\Lambda^\pm = (\Lambda \pm |\Lambda|)/2$$

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Modified Steger-Warming Flux



$$F_{i+1/2} = \underbrace{\frac{1}{2} (R^{-1} \Lambda R)_{i+1/2} (U_{i+1} + U_i)}_{\text{convection}} + \underbrace{\frac{1}{2} (R^{-1} |\Lambda| R)_{i+1/2} (U_{i+1} - U_i)}_{\text{dissipation}}$$

Roe flux form

Baseline flux scheme

➤ Original Steger-Warming Flux

For shock waves

➤ Roe Flux

For smooth flows

Using a pressure dependent weight

$$w_{i+1/2} = 1 - \frac{1}{2} \left(\frac{1}{(\delta p)^2 + 1} \right)$$

High-order fluxes are obtained using the MUSCL approach with a weighted least-squares method to compute gradients.

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Low Dissipation Flux



- Existing low-dissipation schemes to predict small turbulent eddies:
 - Skew-symmetric form to reduce the amplitude of the aliasing errors
 - Entropy function for secondary conservation law
- Present approach: Kinetic energy
 - Kinetic energy transport eq. derived from density and momentum eqs.
 - Combined with internal energy: $\rho E = \rho C_v T + \frac{\rho}{2} u^2$

Kinetic energy consistent flux

$$\sum_f (\rho k u' S)_f = \sum_f \frac{1}{2} (u_i u_{i+1} + v_i v_{i+1} + w_i w_{i+1}) (\rho u' S)_f$$

Dissipative term from the modified Steger-Warming flux

$$d_{i+1/2} = \alpha \frac{1}{2} (R^{-1} |\Lambda| R)_{i+1/2} (U_{i+1} - U_i) \quad \alpha = \frac{(\nabla \cdot \vec{u})^2}{(\nabla \cdot \vec{u})^2 + \|\vec{\omega}\|^2}$$

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Implicit Time Integration



Point Relaxation

Baseline Scheme

$$(I + A_{i+1/2,j}^+ - A_{i-1/2,j}^- + B_{i,j+1/2}^+ - B_{i,j-1/2}^-) \delta U_{i,j} = H_{i,j}$$

$$+ A_{i-1/2,j}^+ \delta U_{i-1,j} - A_{i+1/2,j}^- \delta U_{i+1,j} + B_{i,j-1/2}^+ \delta U_{i,j-1} - B_{i,j+1/2}^- \delta U_{i,j+1}$$

Line Relaxation

For laminar sublayers only

(Modified Steger-Warming flux)

$$B_{i,j+1/2}^- \delta U_{i,j+1} + (I + A_{i+1/2,j}^+ - A_{i-1/2,j}^- + B_{i,j+1/2}^+ - B_{i,j-1/2}^-) \delta U_{i,j} - B_{i,j-1/2}^+ \delta U_{i,j-1} = H_{i,j}$$

$$- A_{i+1/2,j}^- \delta U_{i+1,j} + A_{i-1/2,j}^+ \delta U_{i-1,j}$$

Data-Parallel Relaxation

$$(\tilde{A}^n - \tilde{C}^n) \delta U^k = H^n - \tilde{C}^n \delta U^{k-1}$$

$$\delta U^{n+1} = \delta U^{k \max}$$

- Original Gauss-Seidel not parallelizable
- Replace the G-S sweeps with a series of point Jacobi-like iterations or a series of line relaxations.
- Second order dual time stepping (KEC flux)

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Detached Eddy Simulation



Spalart-Allmaras 1-eq. model with compressibility correction

$$\frac{D\rho\tilde{\nu}}{Dt} = \underbrace{\nabla \cdot \left(\frac{1}{\sigma} \mu \nabla \tilde{\nu} \right)}_{\text{diffusive transport}} + \underbrace{\nabla \cdot \left(\frac{1}{\sigma} \sqrt{\rho\tilde{\nu}} \nabla \sqrt{\rho\tilde{\nu}} \right)}_{\text{diffusive transport}} + \underbrace{\frac{c_{b2}}{\sigma} \nabla \sqrt{\rho\tilde{\nu}} \cdot \nabla \sqrt{\rho\tilde{\nu}}}_{\text{production}} + \underbrace{c_{b1} \tilde{S} \rho \tilde{\nu}}_{\text{production}} - \underbrace{c_{wl} f_w \rho \left(\frac{\tilde{\nu}}{d} \right)^2}_{\text{destruction}}$$

- RANS approach over-predicts the turbulent dissipation levels in separated flow regions.

- DES introduces a new length scale $\tilde{d} = \min(d, C_{DES} \Delta)$

- *Model behaves like a subgrid scale model for LES away from the wall.*
- Wall-Modeled LES

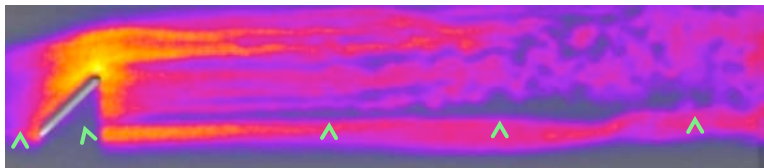
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Test Case



NASA LaRC Mach 10 wind tunnel experiment by Danehy et al.



Laminar
Flow

BLT Trip

Streak
Instabilities

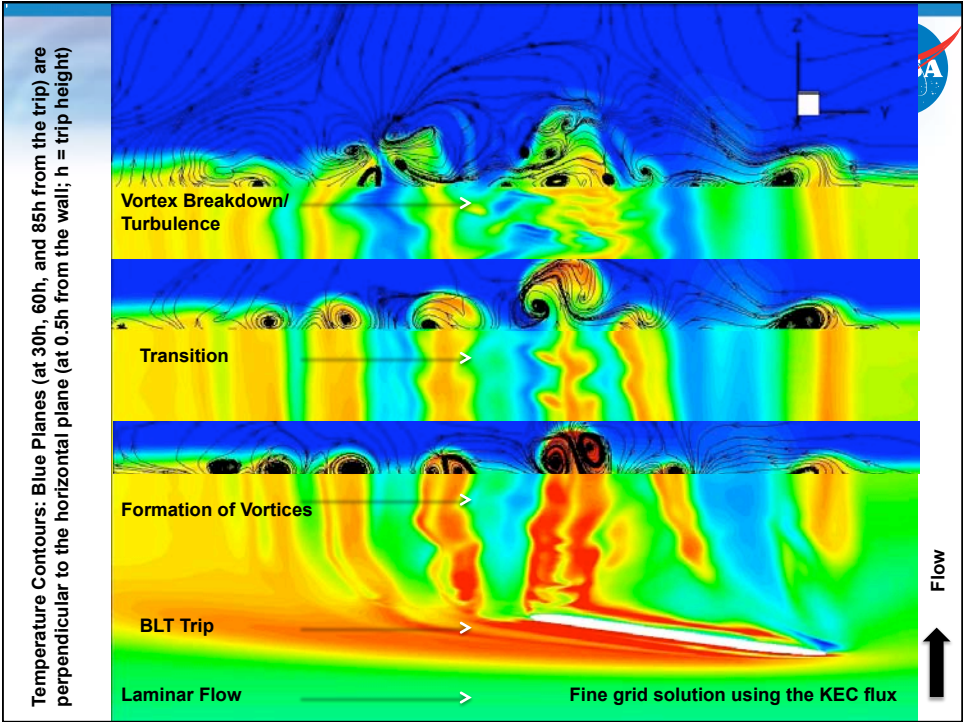
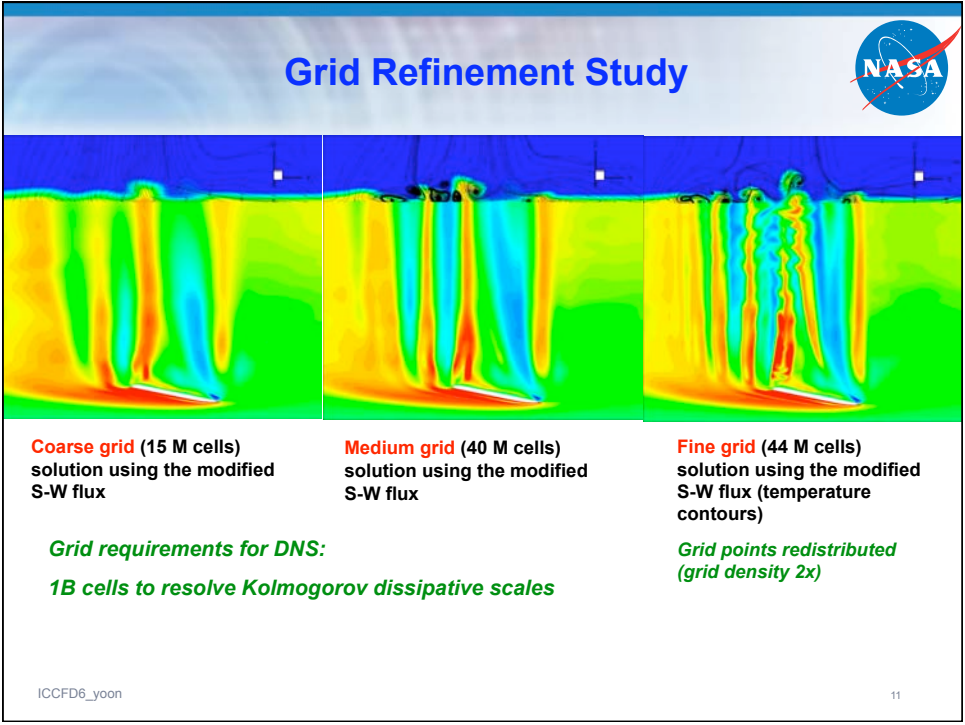
Transition

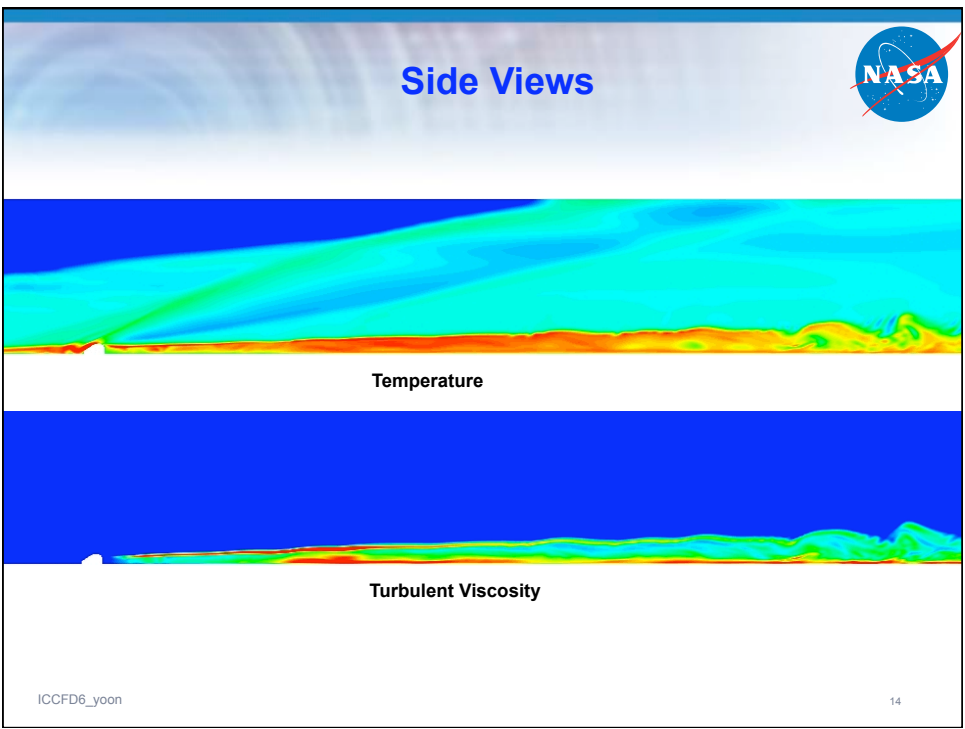
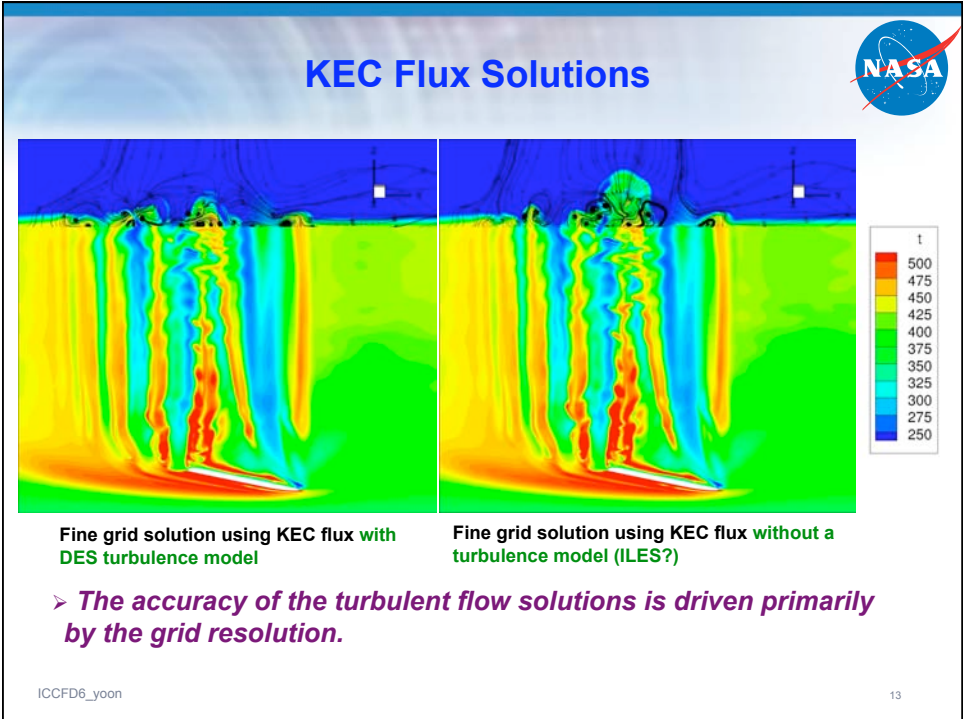
Turbulent
Flow

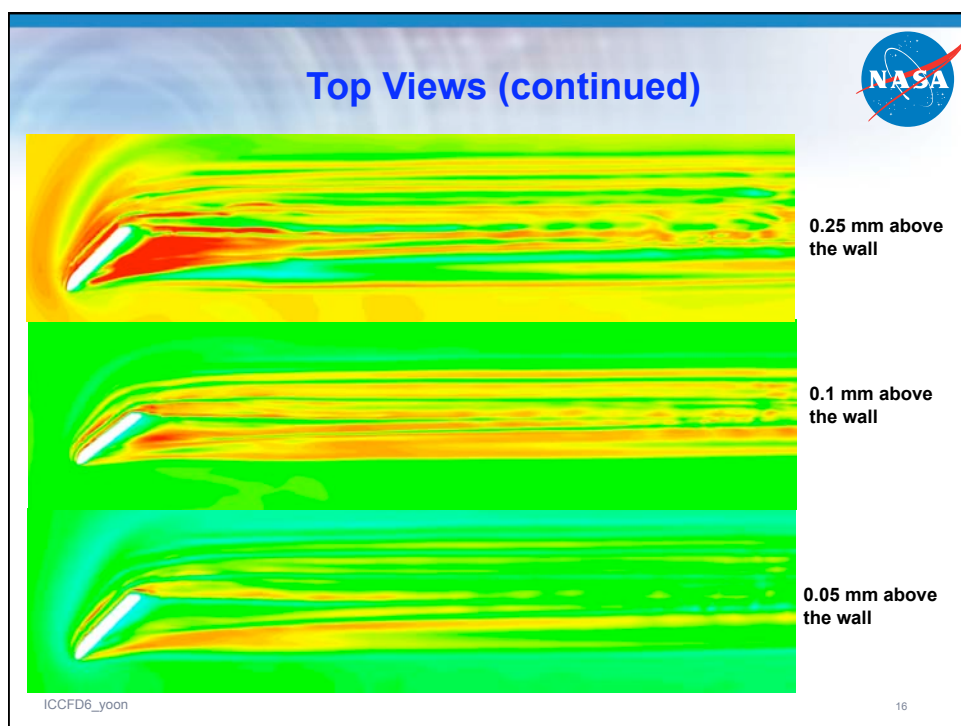
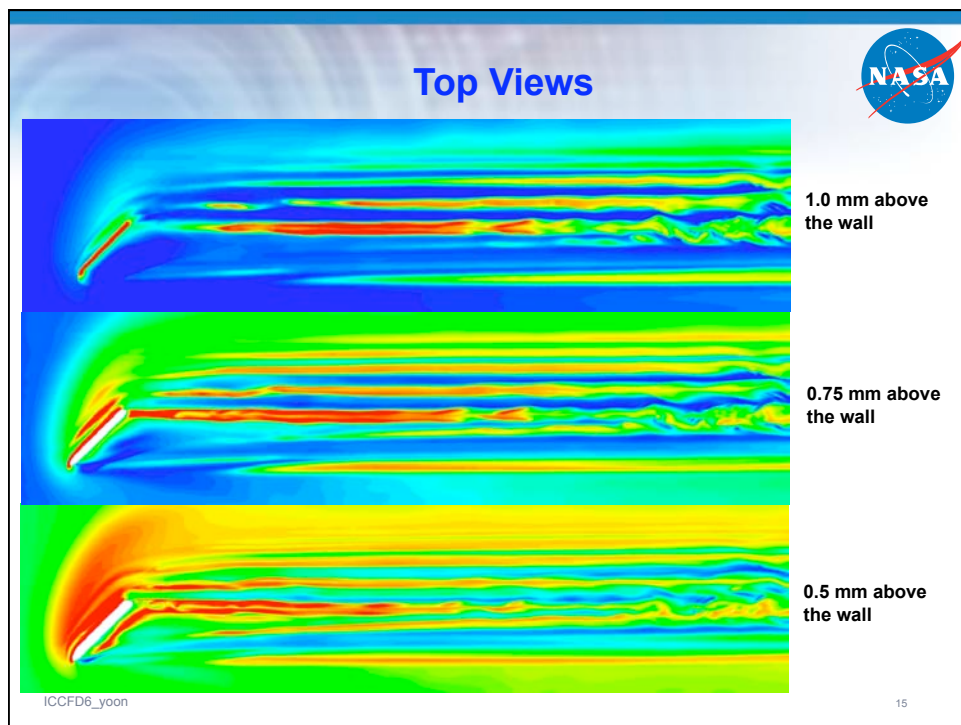
Flow conditions: $M_{inf} = 9.93$, $Re_k \sim 6,000$, $T_{inf} = 51.3K$, $T_w = 308K$

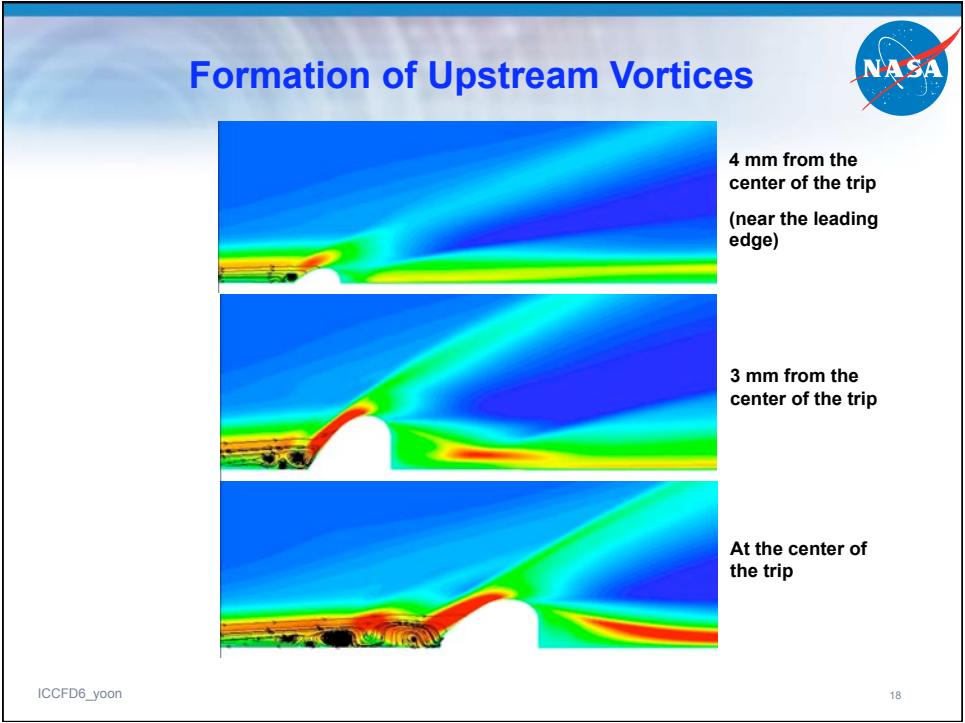
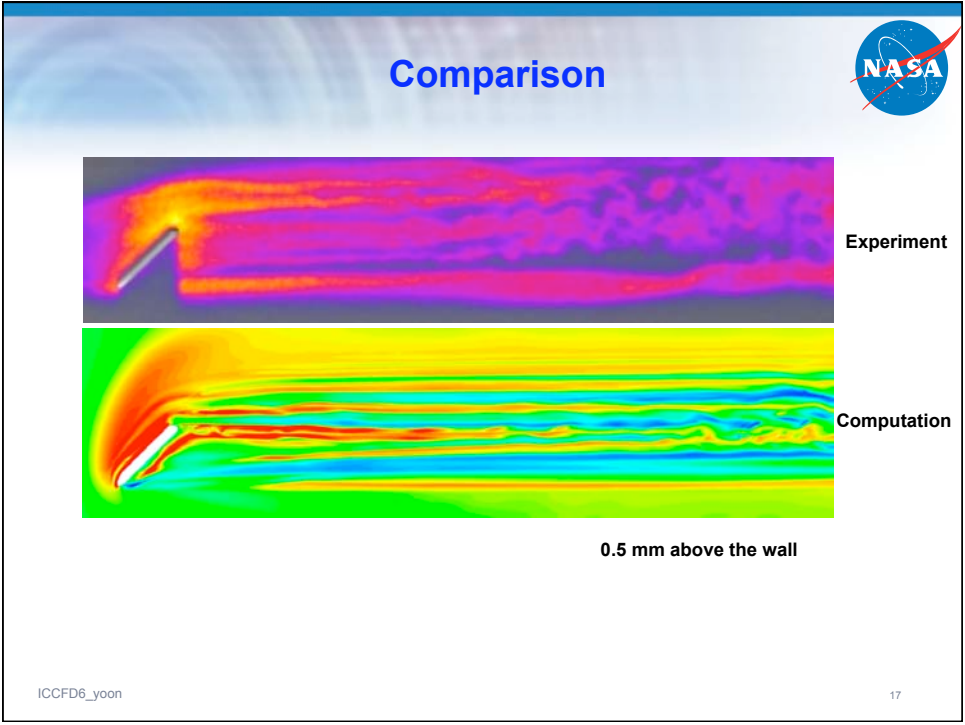
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Conclusions



- **DES/ WMLES/ Hybrid RANS-LES can be a useful tool for predictions of hypersonic boundary layer transition to turbulence triggered by an isolated roughness element.**
- **It is necessary to use the low-dissipation kinetic energy consistent scheme on a sufficiently fine grid for an accurate simulation of transition.**
- **Accuracy of the turbulent flow solutions is driven primarily by the grid resolution.**
- **Interaction of vortices leads to vortex breakdown and hence turbulent flow.**
- **Computational results agree well qualitatively with the experimental observations.**

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